Radiation Safety Considerations for Replacement of the Soft X-Ray Undulators for LCLS-II-HE

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Outline

SLAC and LCLS-II-HE Overview

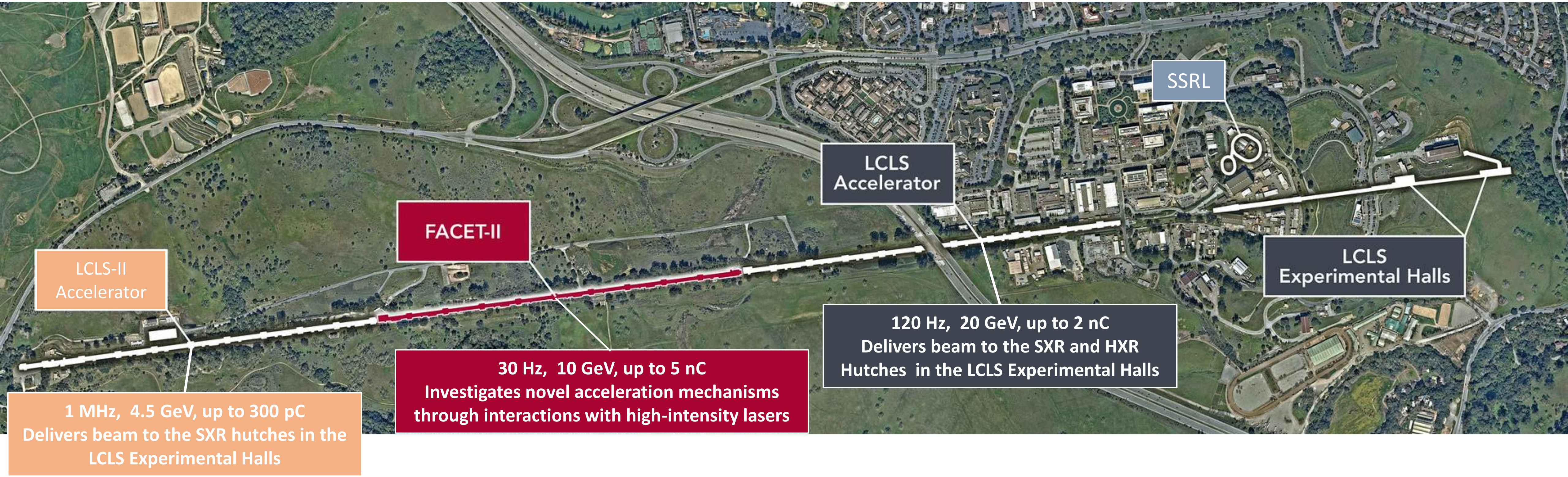
Defining the Scope of Work

Beam Containment Analysis

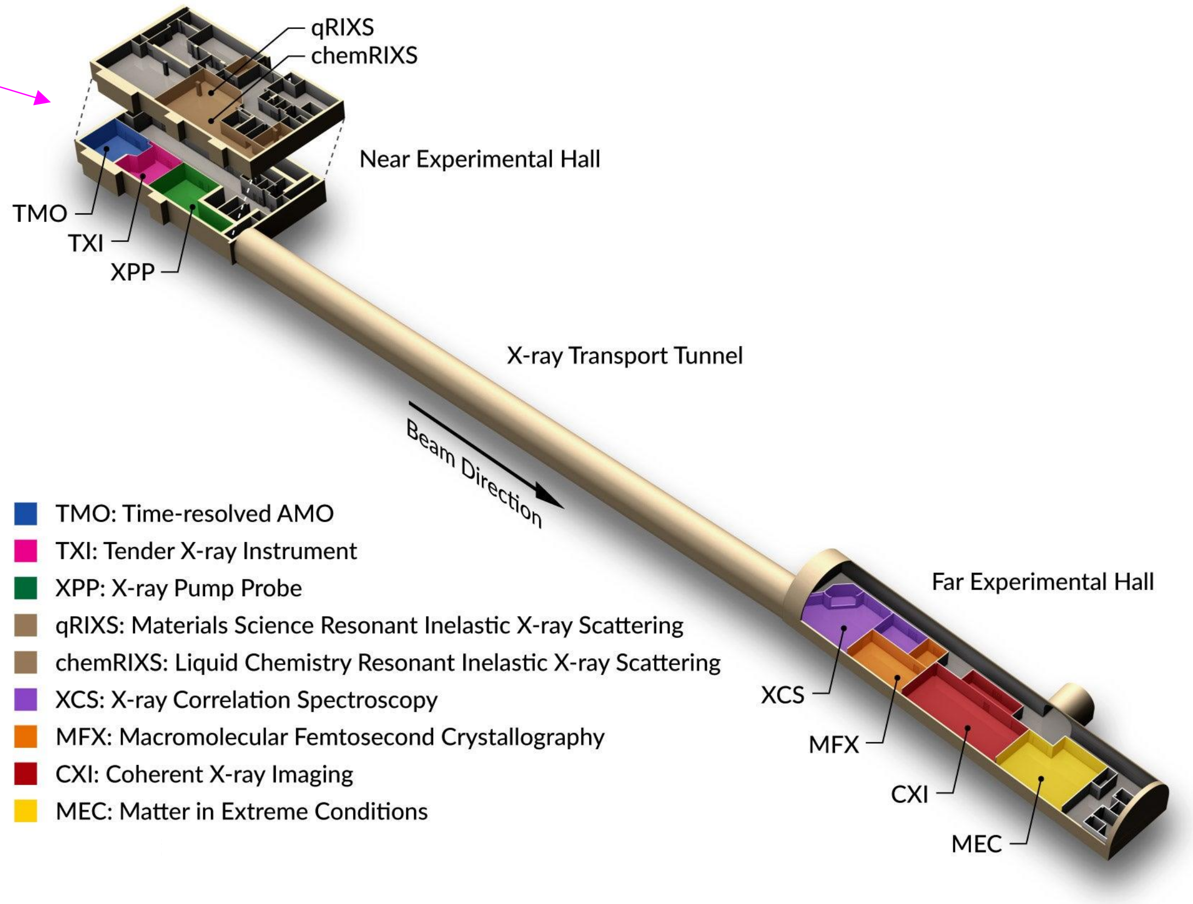
- Superconducting Beam
- Normal Conducting Beam

Shielding Analysis

Linear Accelerator Facility at SLAC



LCLS Experimental Halls and FEL Capabilities



Soft X-Ray Hutches (TMO, RIX, and TXI-SXR) have access to:

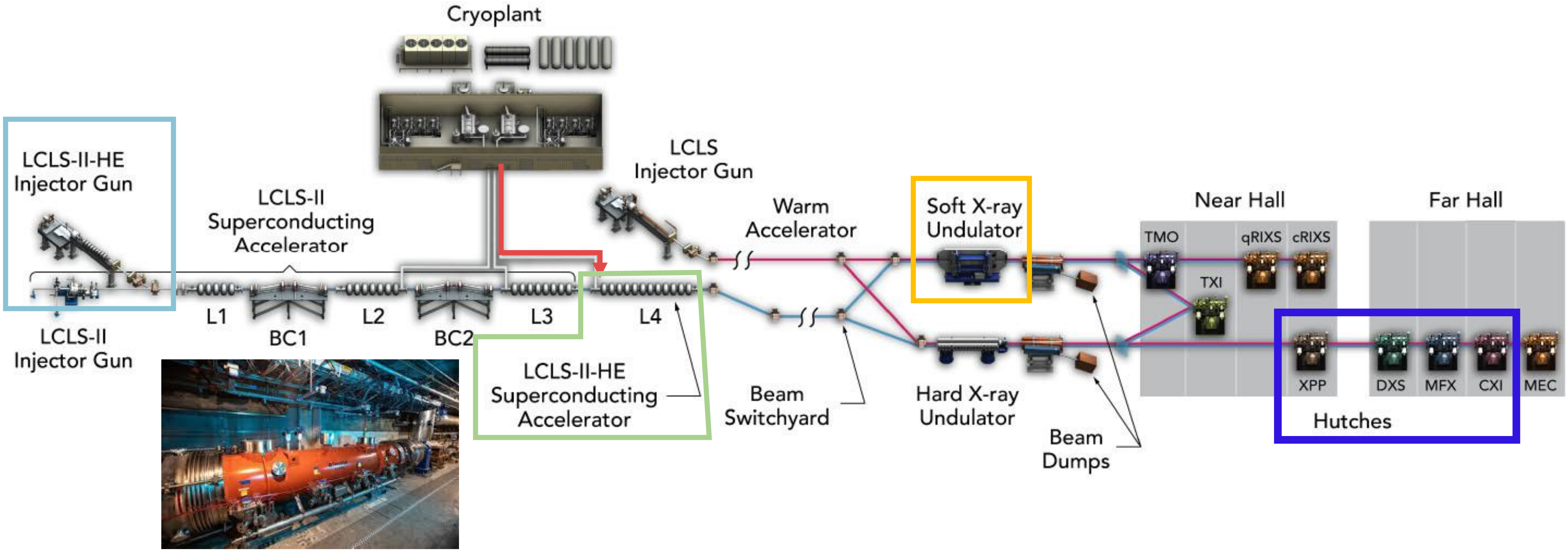
- 250 eV up to 2.1 keV x-rays @ 1 MHz with the LCLS-II
- 250 eV up to 8 keV x-rays @ 120 Hz with the LCLS

Hard X-Ray Hutches (TXI-HXR, XPP, XCS, MFX, CXI, MEC) have access to:

- 1 keV up to 25 keV x-rays @ 120 Hz with the LCLS

The capabilities of all soft and hard x-ray hutches *(except MEC)* **will be upgraded as a part of the LCLS-II High Energy project (LCLS-II-HE)**

LCLS-II HE Project Overview



1. Add 23 additional cryomodules (L4 linac) to double the LCLS-II accelerator energy: 4 GeV to 8 GeV
2. Install new cryogenic distribution box and transfer line between the cryoplant and the new L4 linac
3. New long period soft X-ray undulator (SXU).
4. Design low-emittance injector and SRF gun for extended hard X-ray performance
5. Upgrade the LCLS hard X-ray (HXR) instruments for MHz beam and data rates

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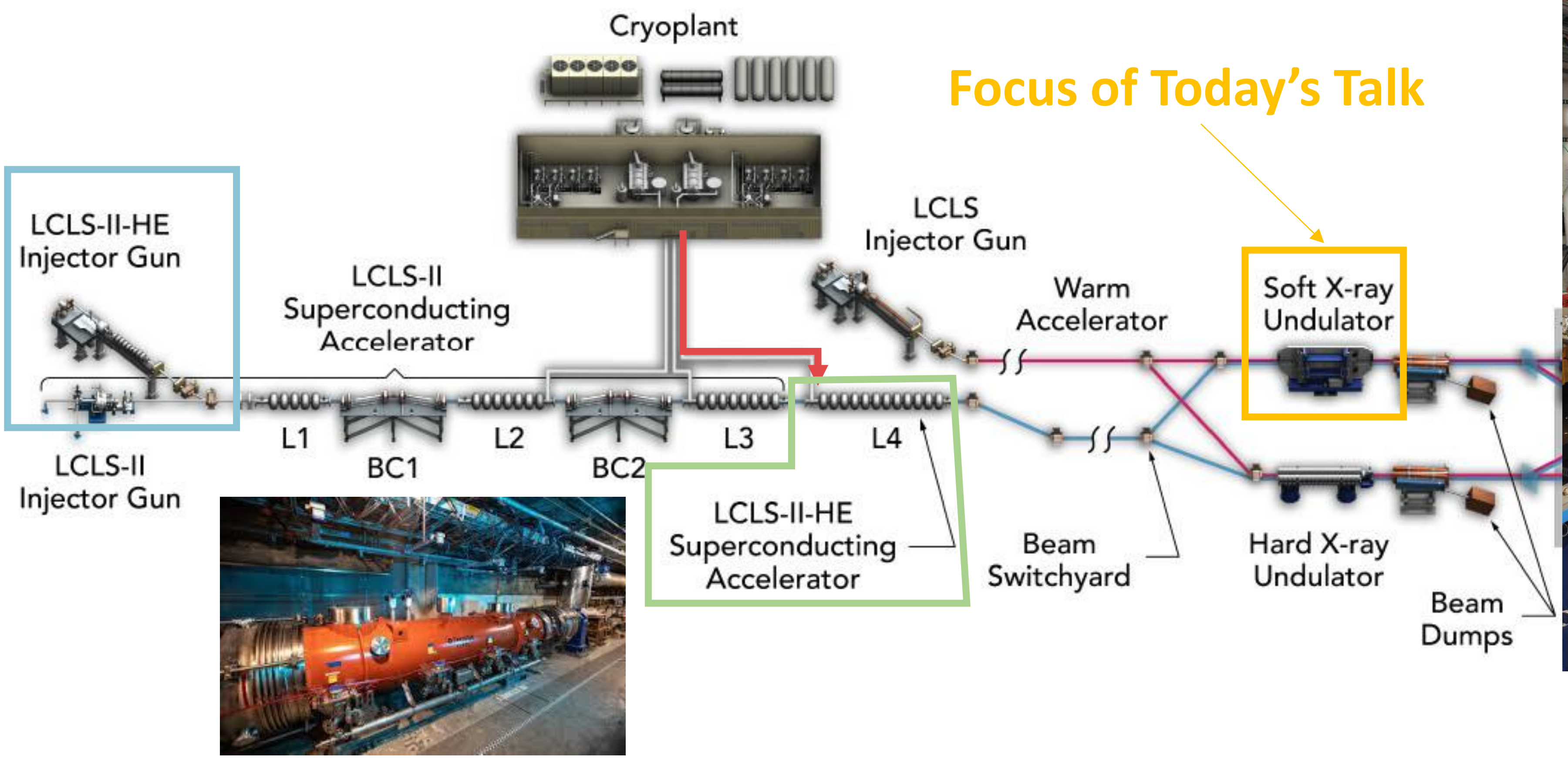

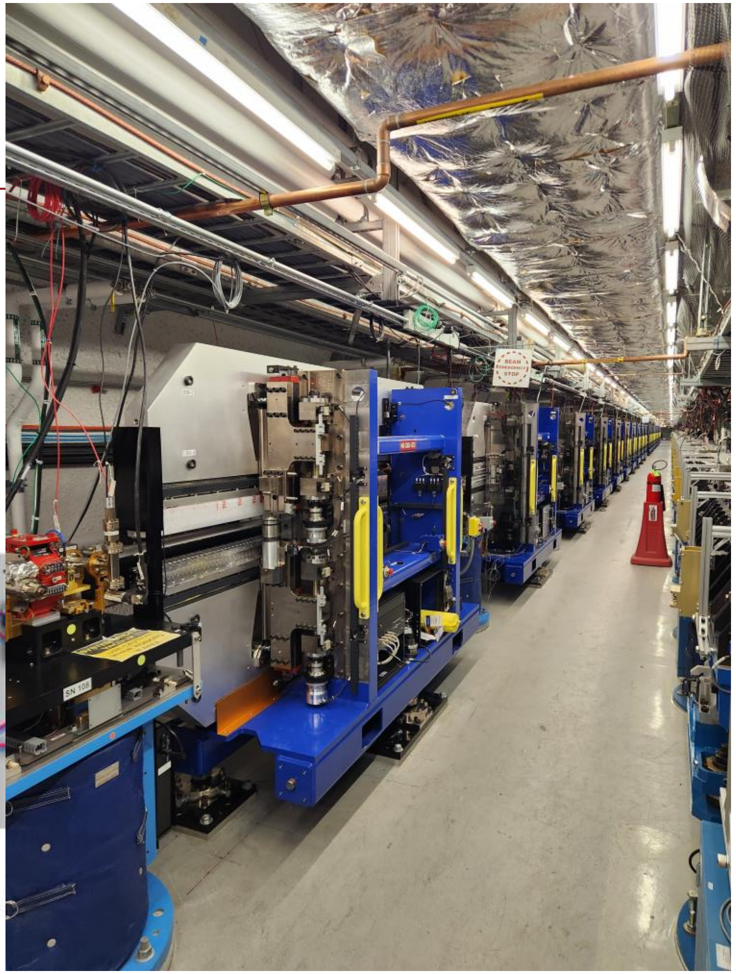

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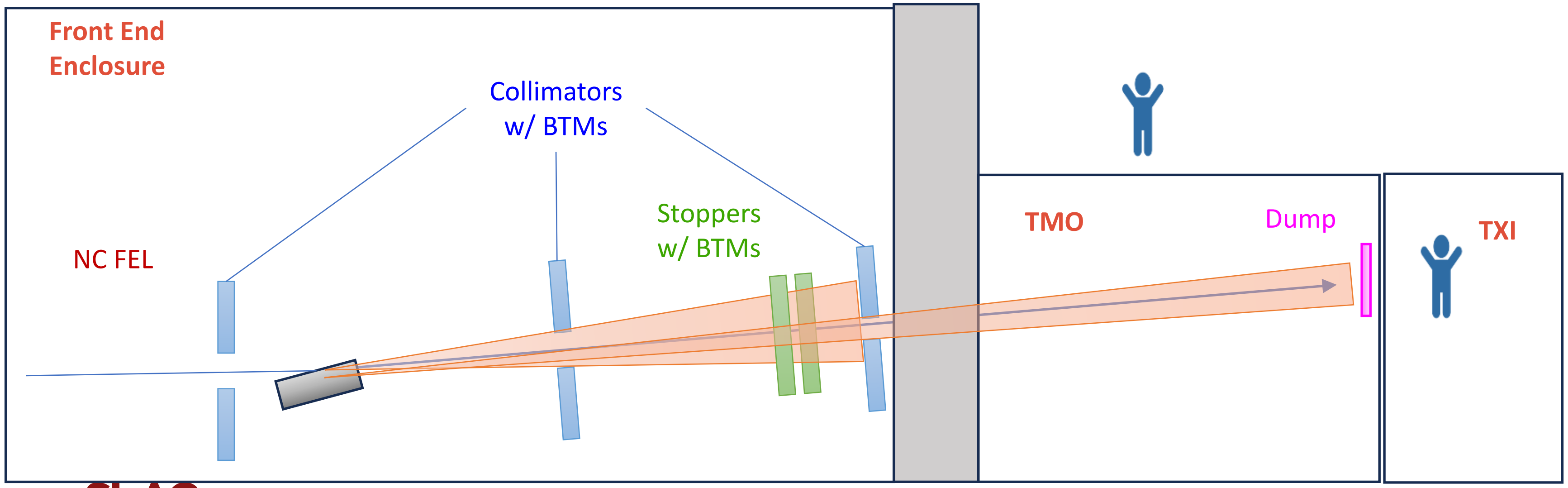
Overview

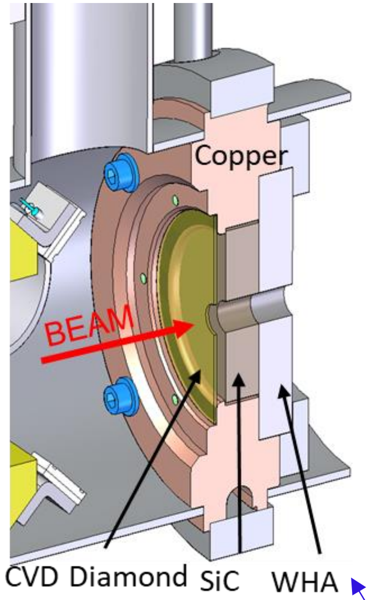
The LCLS-II HE Project plans to change the Soft X-ray Undulators *<u>during the ongoing operation</u>* of the LCLS NC and LCLS-II SC operation, which affects the following:

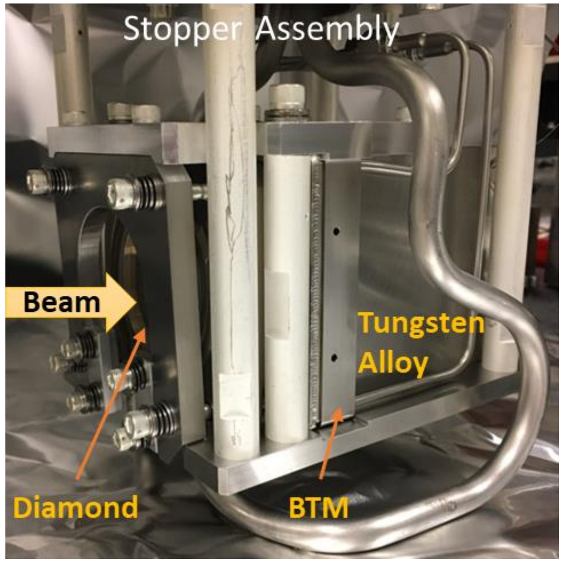
Beam Containment System (BCS)

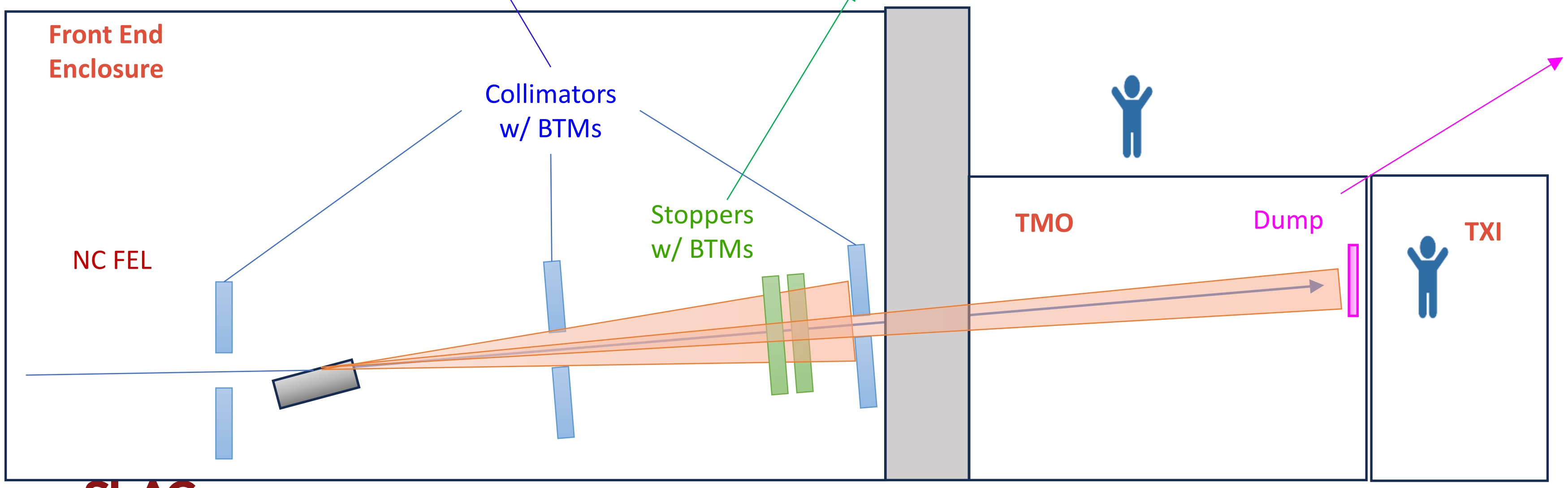
- Ensures that the beam remains in its desired channel
- Change in FEL yield affects assumptions used in BCS Safety Analyses



Overview







BeO Water cooled beam dump

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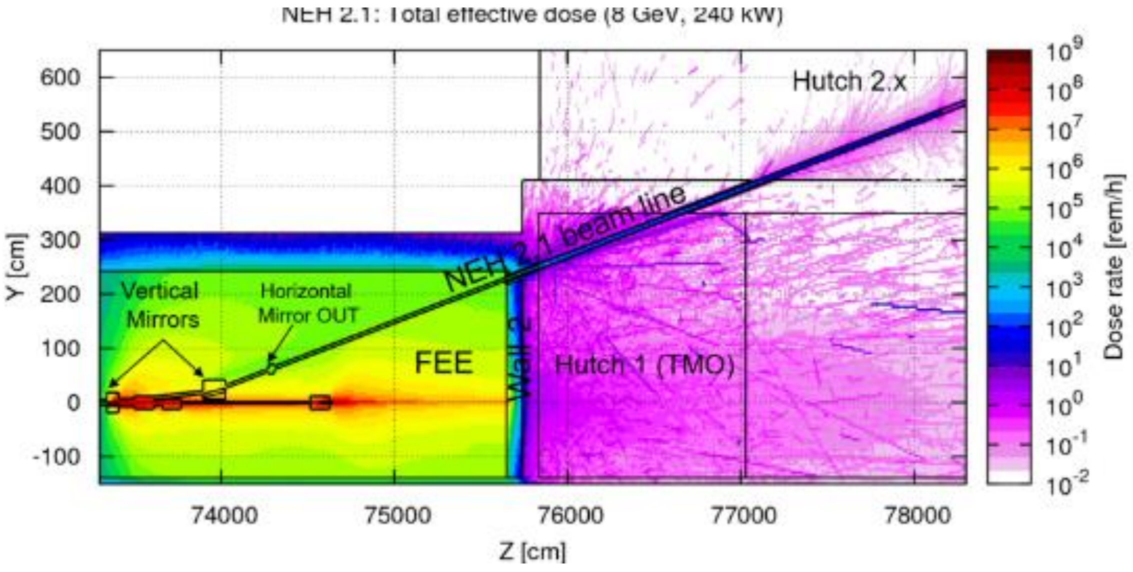
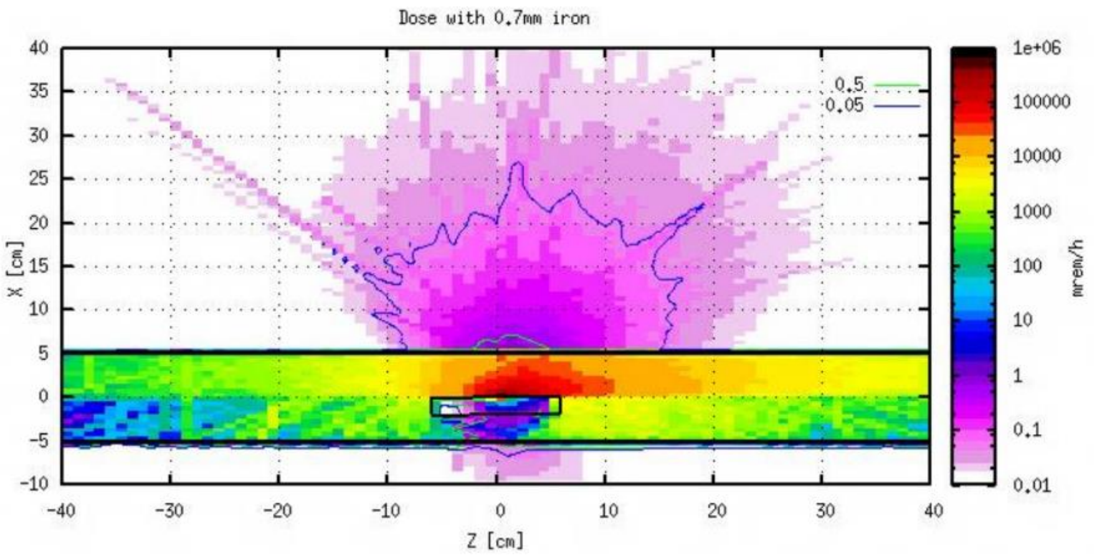
Shielding

- Affects the source term used in radiation shielding calculations



Shielding Studies of the Front End Enclosure



Generalized model of hutch shielding

Overview

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Shielding

- Affects the source term used in radiation shielding calculations

This talk with cover some of the aspects of the analysis performed that enabled the approval of the installation of the new undulators during ongoing operation

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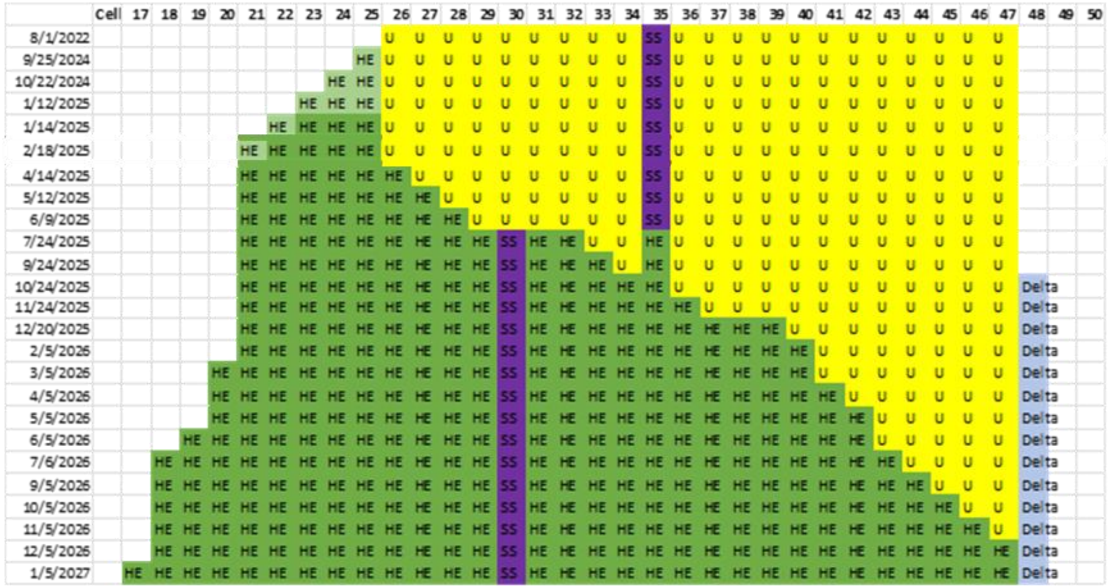
Shielding Analysis

Coordinating Analysis and Work Scope

Planned Installation Schedule



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LCLS-II SXUs (39 mm) | **HE SXUs (56 mm)** | **Self-Seeding (out of scope)** | **Delta Undulator (out of scope)**

Each row represents a unique configuration of the soft x-ray undulator string that could produce FEL Beam and Synchrotron Radiation

Collaboration with the project and FEL scientists is key in defining the scope of work for RP analysis:

- **BCS**: Defining how ***maximum credible FEL parameters*** would change:
  - Pulse Yield
  - Divergence and Source Location
  - Bandwidth
- **Shielding**: Clarity on the installation schedule
  - What would be the maximum number of undulator periods?

Coordinating Analysis and Work Scope

Planned Installation Schedule

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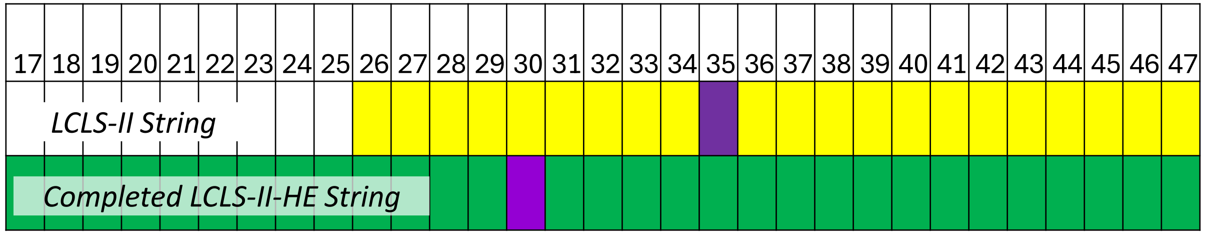
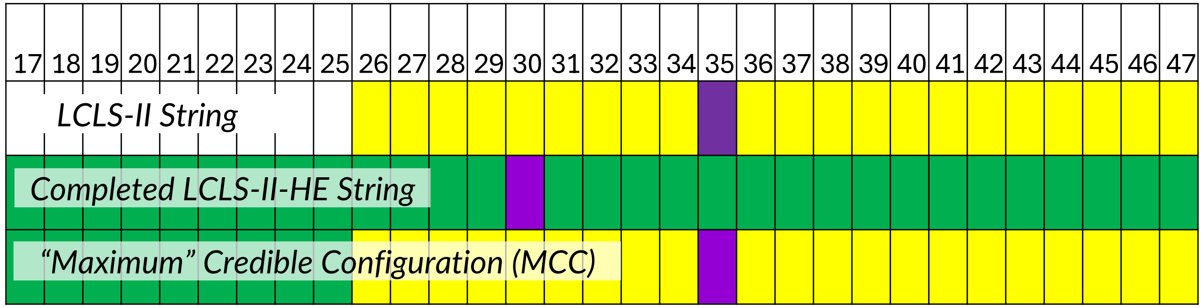
FEL BCS



Bookend cases dominate and mixed undulator stings are expected to produce less FEL

Shielding



Intermediate and potentially not used but bounding "maximum credible configuration" resulted in the largest number of undulator periods

Coordinating Analysis and Work Scope: BCS

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LCLS-II String																														
Completed LCLS-II-HE String																														

<u>For SC FEL:</u>

- Per FEL source term analysis, adopt 25% increase in maximum credible FEL source term for SC operation

<u>For NC FEL:</u>

- The note gives much higher pulse energies (up to 100%) at some photon wavelengths *(details later)*

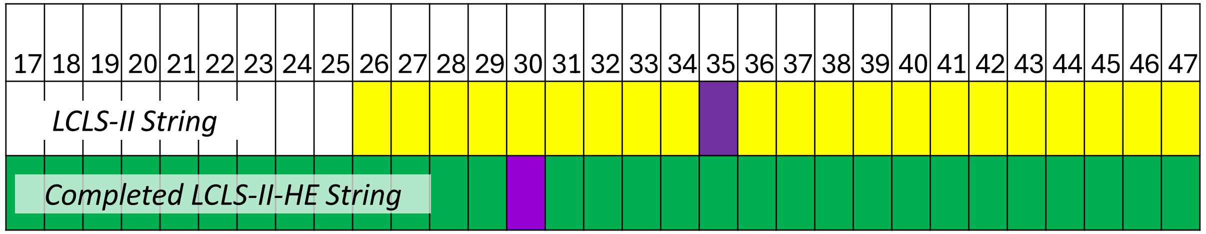
Coordinating Analysis and Work Scope: BCS

Planned Installation Schedule

	Cell	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
8/1/2022											U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
9/25/2024										HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
10/22/2024									HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
1/12/2025								HE	HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
1/14/2025							HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
2/18/2025						HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
4/14/2025						HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
5/12/2025						HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
6/9/2025						HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
7/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	U	U	HE	U	U	U	U	U	U	U	U	U	U	U	U			
9/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	U	HE	U	U	U	U	U	U	U	U	U	U	U	U			
10/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	U	U	U	Delta		
11/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	U	U	Delta		
12/20/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	Delta		
2/5/2026						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	Delta		
3/5/2026					HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	Delta		
4/5/2026					HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	Delta		
5/5/2026					HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	Delta		
6/5/2026				HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	Delta		
7/6/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	Delta		
9/5/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	Delta		
10/5/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	Delta		
11/5/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	Delta		
12/5/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	Delta		
1/5/2027		HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	Delta		

LCLS-II SXUs (39 mm) **HE SXUs (56 mm)** **Self-Seeding (out of scope)** **Delta Undulator (out of scope)**

Each row represents a unique configuration of the soft x-ray undulator string that could produce FEL Beam and Synchrotron Radiation



Planned Power Ramp up before Long Down Time for LCLS-II-HE:

- Nominal electron beam of 20 kW to the dumps
- Corresponds to maximum electron beam of 26.6 kW

The analysis will extend up to 27 kW e- beam at 4.5 GeV

Goal: Results demonstrate expected safety margins at this power

Limiting to a certain power helped to streamline the approval process, as average FEL powers remained within previously studied domains

Coordinating Analysis and Work Scope: Shielding

Planned Installation Schedule

	Cell	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
8/1/2022											U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
9/25/2024										HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
10/22/2024									HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
1/12/2025								HE	HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
1/14/2025							HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
2/18/2025						HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
4/14/2025						HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
5/12/2025						HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
6/9/2025						HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	SS	U	U	U	U	U	U	U	U	U	U	U	U			
7/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	U	U	HE	U	U	U	U	U	U	U	U	U	U	U	U			
9/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	U	HE	U	U	U	U	U	U	U	U	U	U	U	U			
10/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	U	U	U	Delta		
11/24/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	U	U	U	Delta		
12/20/2025						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	U	Delta		
2/5/2026						HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	Delta		
3/5/2026					HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	U	Delta		
4/5/2026					HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	U	U	Delta		
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7/6/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	U	U	Delta		
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10/5/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	U	U	Delta		
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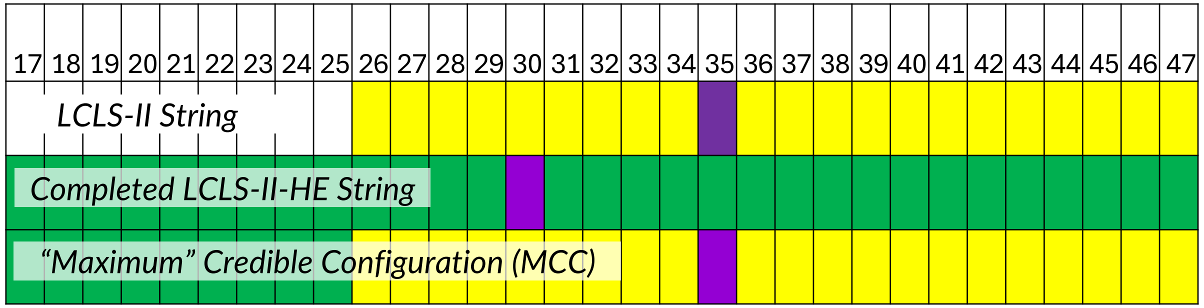
12/5/2026			HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	Delta		
1/5/2027		HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	SS	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	HE	Delta		

LCLS-II SXUs (39 mm) | HE SXUs (56 mm) | Self-Seeding (out of scope) | Delta Undulator (out of scope)

Each row represents a unique configuration of the soft x-ray undulator string that could produce FEL Beam and Synchrotron Radiation



Assess shielding impact as defined by Accelerator Safety Envelope:

- NC Linac: **12 GeV** and **2.6 kW** on the SXR line
- SC Linac: **5 GeV** and **120 kW** on the SXR line

Outline

SLAC and LCLS-II-HE Overview

Defining the Scope of Work

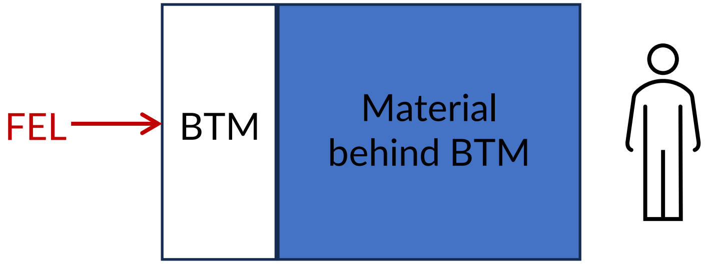
Beam Containment Analysis

- Superconducting Beam
- Normal Conducting Beam

Shielding Analysis

SC FEL Safety Analysis Consideration:

1. Stopper needs to take SC FEL Beam indefinitely:
    a. **Thermomechanical Survival** at High average power
    b. Combination of high pulse energies and high FEL power may cause **slow sublimation** of the stopper
2. Interlock response needs to be fast enough to prevent the beam from reaching accessible areas:
    a. **Burnthrough time** of backing material in stoppers, collimators, and dumps is used to hold the FEL beam while the BTM responds
    b. BTM or vacuum interlock response time
3. Air is used to attenuate the FEL and protect people in accessible areas
    a. Tunneling Effect can increase transmission



FEL analysis demonstrates that beam size is not expected to change.

Need to reconsider with SC FEL pulse energy (and therefore average FEL power) increased by 25%

SC FEL Safety Analysis Consideration:

1. Stopper needs to take SC FEL Beam:
   a. Thermomechanical Survival at High average power – Steady State thermal analysis
   b. Combination of high pulse energies and high FEL power may cause slow sublimation of the stopper
2. Interlock response needs to be fast enough to prevent the beam from reaching accessible areas:
   a. Burnthrough time of backing material in stoppers, collimators, and dumps is used to hold the FEL beam while the BTM responds
   b. BTM or vacuum interlock response time
3. Air is used to attenuate the FEL and protect people in accessible areas
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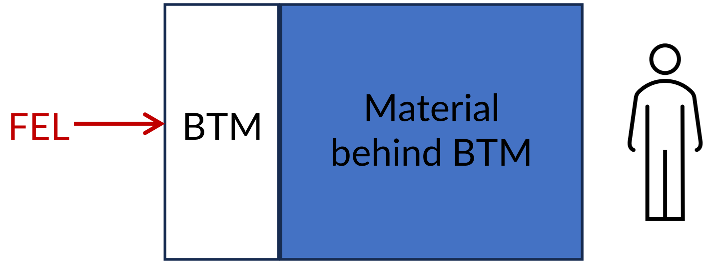
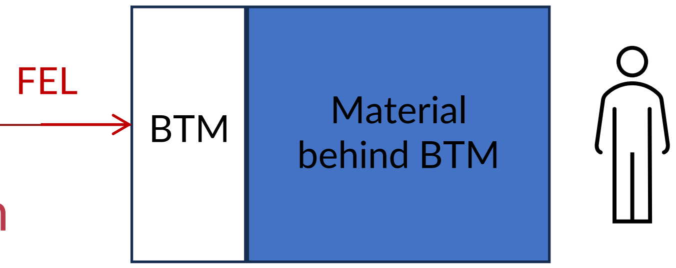


FEL analysis demonstrates that beam size is not expected to change.

Need to reconsider with SC FEL pulse energy (and therefore average FEL power) increased by 25%

Burnthrough Time Calculation



A simple conservative model is used to predict the complex burnthrough time phenomena:

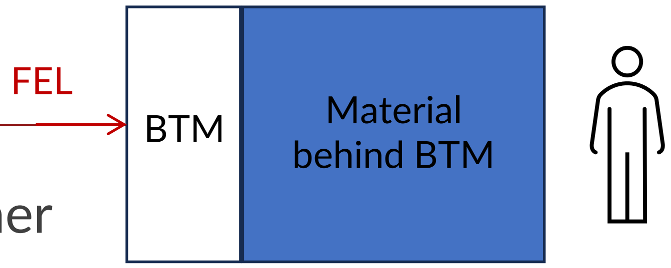
$$Drill\ Speed = \frac{FEL\ Power}{\frac{2\pi\sigma^2\rho H}{A}}$$

σ = rms beam size, ρ = density, A = atomic mass number, H = total energy needed to vaporize 1 mole of material

Model assumes:

- No heat transfer
- Does not consider any effects related to material clearance from the channel
- Independent of changing attenuation length → Surface heating instead of volumetric heating

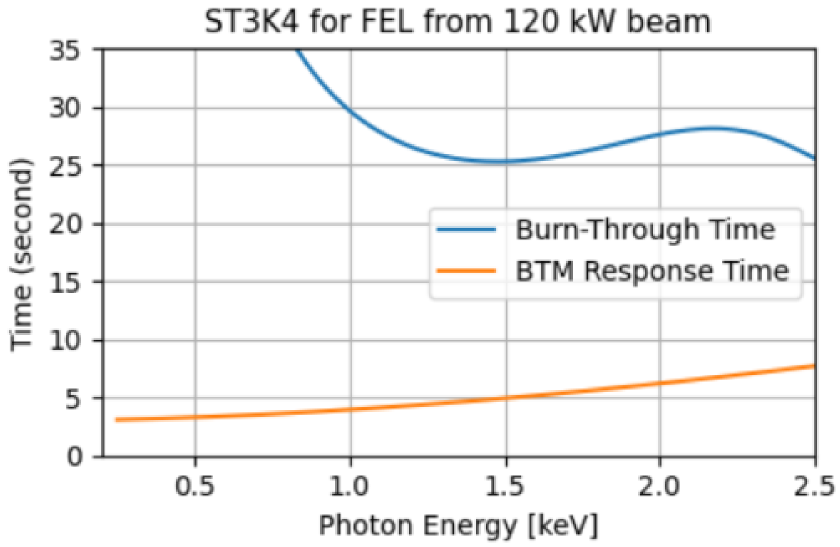
Interlock Response Time Calculation

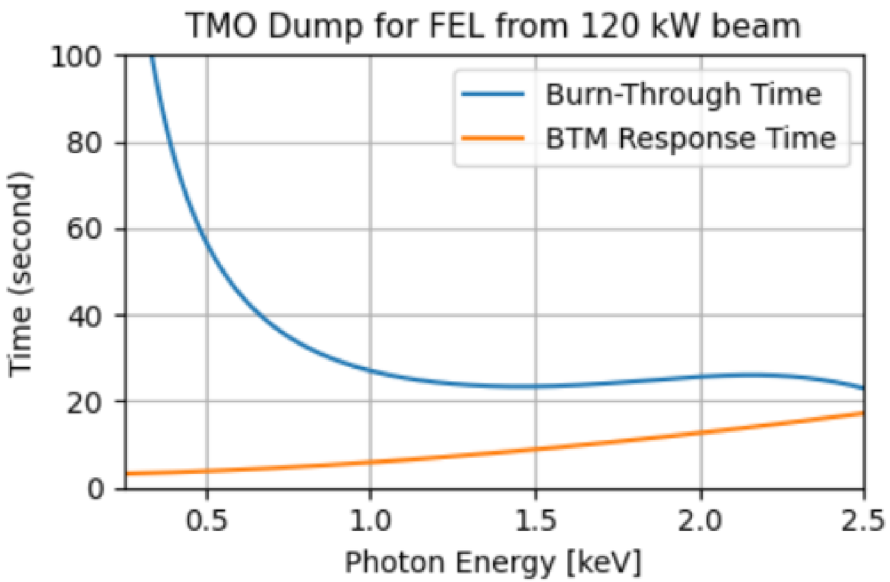


Burnthrough monitors (BTMs) used in LCLS-II BCS systems are a container with pressurized gas.

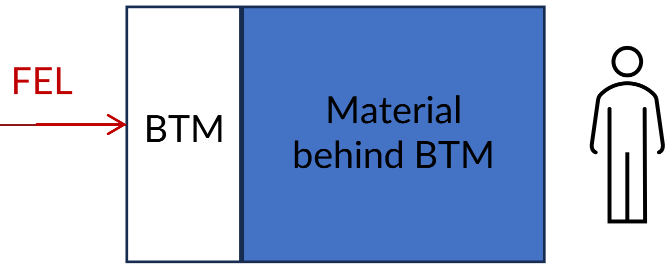
- When a hole is drilled in the BTM, a sensor will detect the pressure change due to the gas escaping through the hole

Assumed: Hole size is assumed to be equal to the FEL FWHM which changes as a function of FEL energy

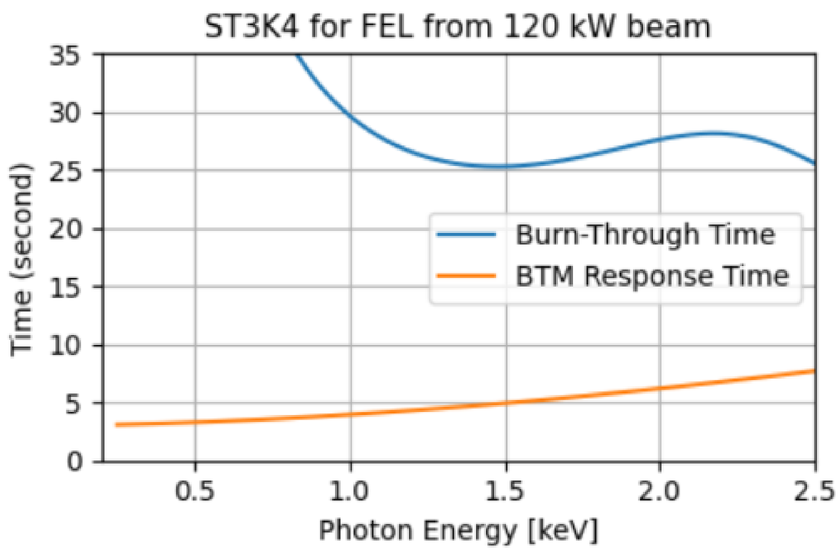


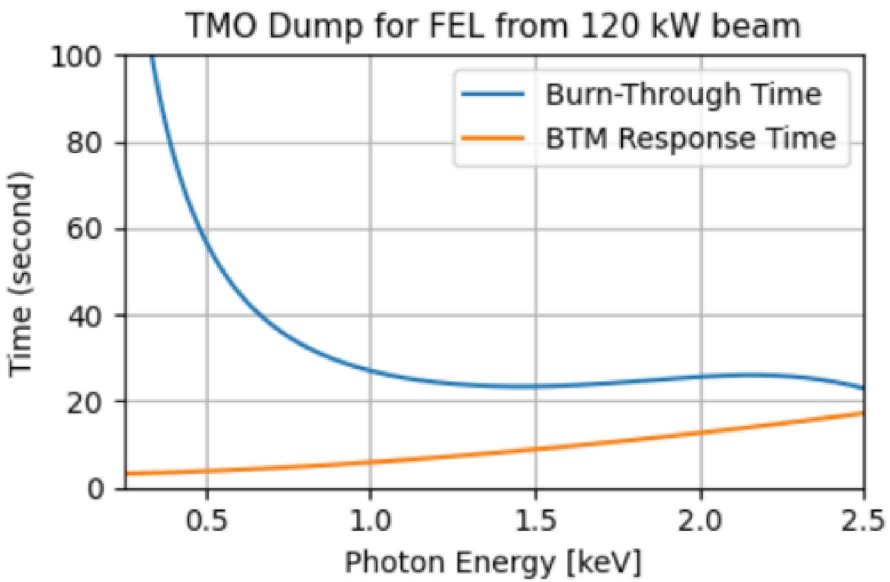


Interlock Response Time Calculation

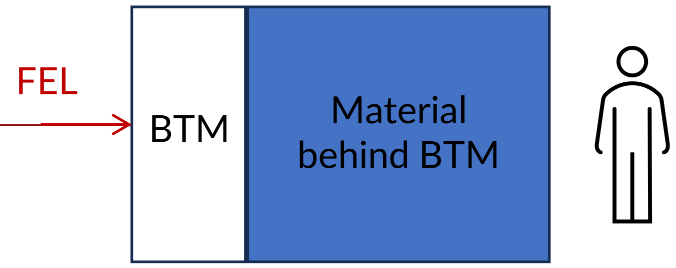


Conservative Safety Margin can be developed by taking the ratio of the two values at their minimum separation





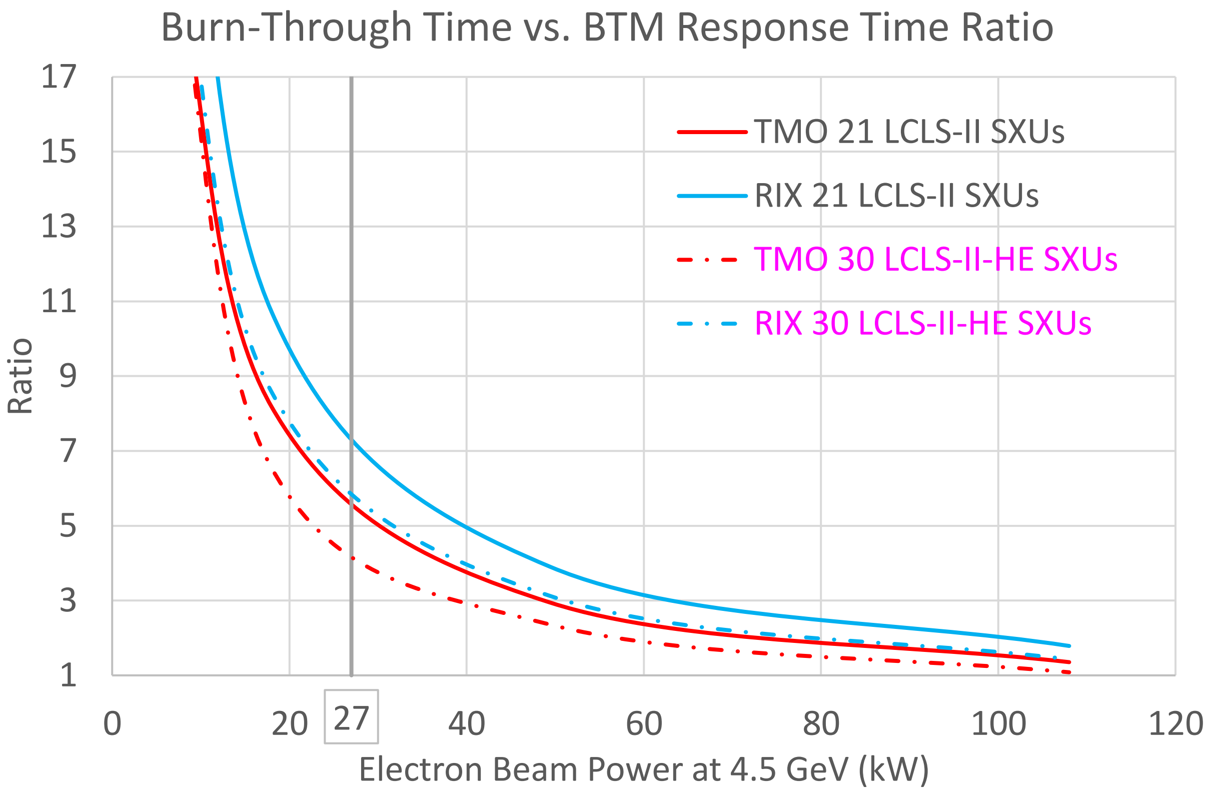
Interlock Response



Change to expected safety margin:

a. Hole's size produced in BTM or vacuum boundary
   - *No change to beam size, so the response is unaffected*

b. Burnthrough time of backing material (*BTM only*)
   - *25% increase in average FEL Power and no change in beam size*



Limiting Cases are the TMO dump and RIX Stopper

The expected **minimum safety factor for the interlock response is >4 for the TMO dump at 27 kW e-beam and the maximum theoretical FEL yield**

Bootstrap test will be performed ramping up to this level

Outline

SLAC and LCLS-II-HE Overview

Defining the Scope of Work

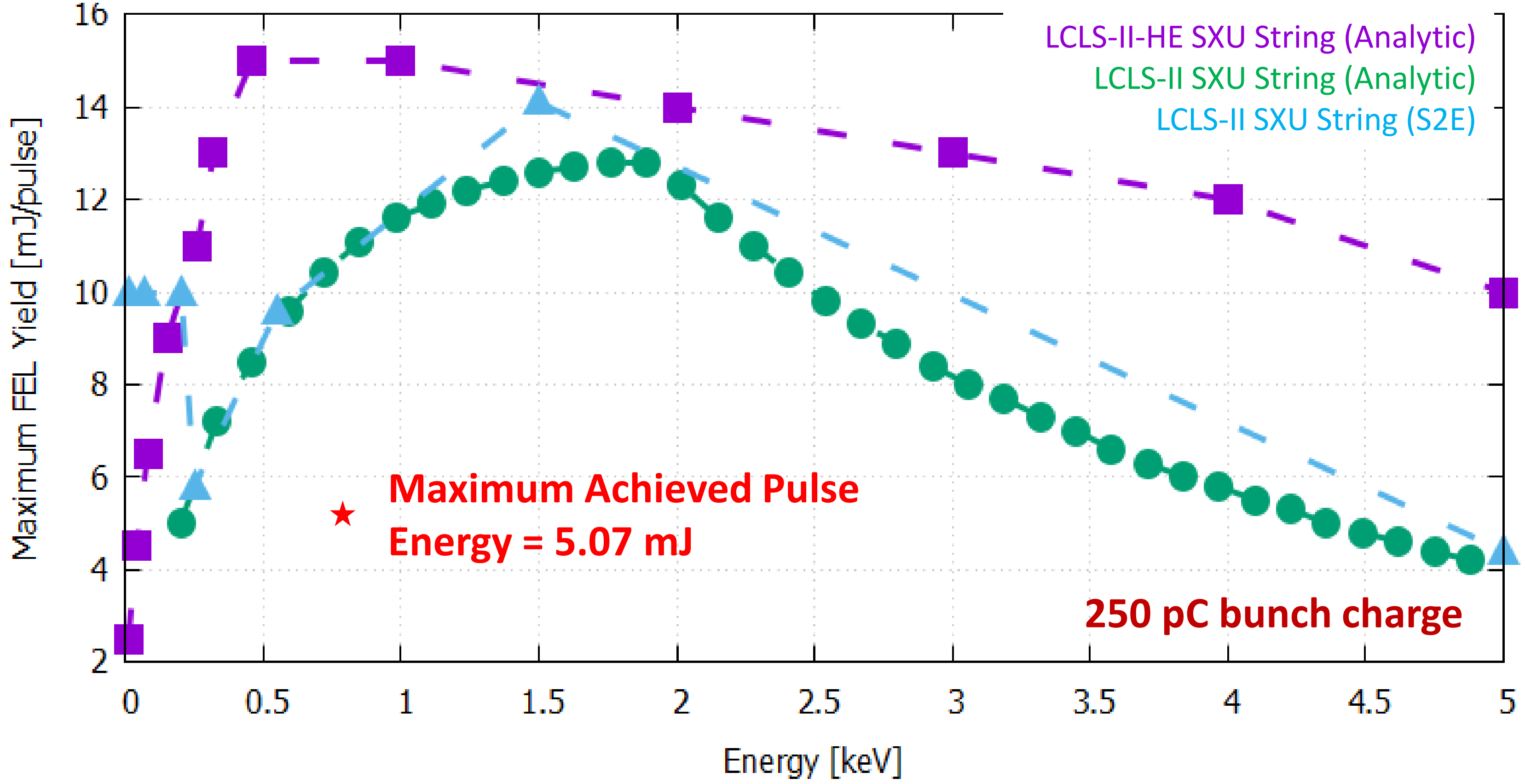
Beam Containment Analysis

- Superconducting Beam
- Normal Conducting Beam

Shielding Analysis

Beam Containment: NC FEL Yield

Analysis shows that FEL yield during NC Operation will increase significantly



NC FEL BCS Analysis

The hazard from NC-FEL operation is **multi-pulse damage** which will be assessed for relevant BCS components

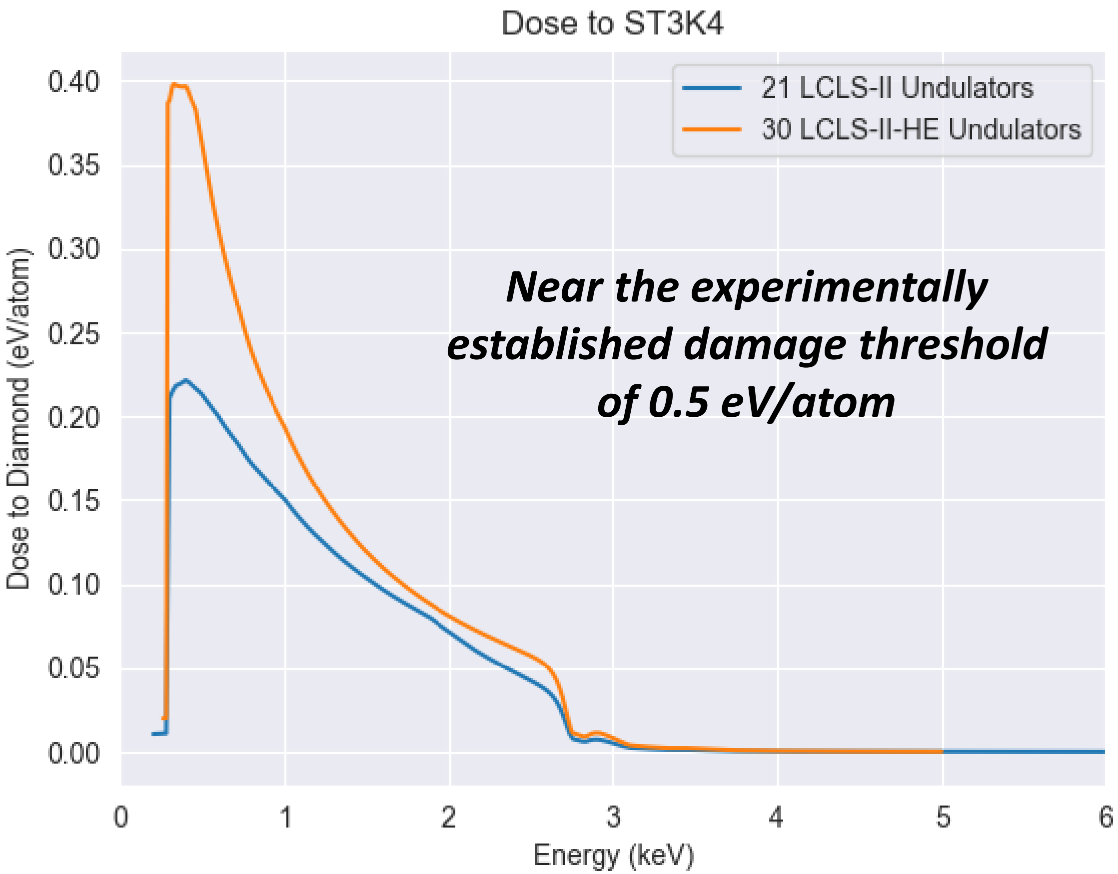
- CVD Diamond in stoppers ST1K2 (RIX), ST1K3 (TXI-SXR), and ST3K4 (TMO)
- CVD Diamond in Collimator PC2K4 (TMO)
- SiC in Collimator PC1K3 (TXI-SXR)

Multibunch operation will also be investigated and can send up to 8 electron bunches in a short bunch train

- Previous analysis limits the operation to $\leq$ 4 bunches

Simulations of Dose [eV/atom] will be compared to experimentally measured damage thresholds to determine if additional controls are needed

NC FEL Beam Containment: TMO Stopper (ST3K4)



Stoppers and collimators survive single pulse damage effects during operation at the maximum credible yield

However, the **factor of ~2 increase in maximum credible FEL pulse energy** leads to significantly higher dose to BCS components

Previously developed limits on multibunch operation need to be revised to address the increased FEL yield

Summary of Beam Containment Hazards

Beamline	Component	SC FEL (300 pC)	NC FEL (250 pC/bunch)	
			Single Bunch	Multibunch Operation
RIX	Diamond Stopper ST1K2	OK up to 27 kW of e- beam with safety margins	OK	Limits Needed (Limiting Case)
TMO	Diamond Stopper ST3K4		OK	Limits Needed
	Diamond Collimator PC2K4		OK	Limits Needed
TXI	SiC PC1K3	*Out of Scope*	OK	Limits Needed

SC FEL: Existing monitoring and Testing for SC-FEL as a part of the bootstrap plan is sufficient up to 27 kW of e- beam *(and likely beyond given current FEL yields)*

NC FEL: 12 mJ/bunch-train FEL yield limits is needed (ST1K2 is the limiting case)

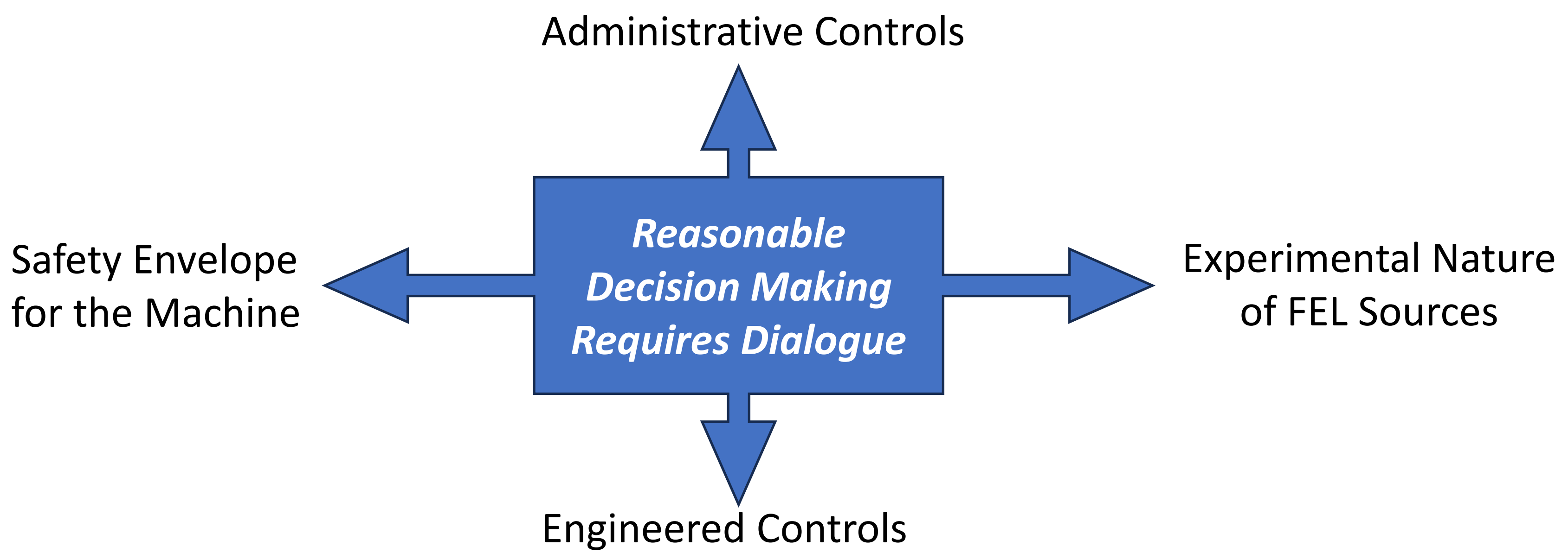
- Collaborative and regular monitoring program with the Accelerator Directorate and LCLS Organization is a reasonable path forward to control low probability hazard of prolonged high FEL yields or infrequent multibunch operation on the SXR line

Comments on FEL BCS Analysis

Paradigm of defining maximum credible beam (required by US regulatory body) works well for accelerators (i.e. electrons) but not so well for FEL

- Specialized expertise required to produce and interpret FEL source simulations
- Path to achieving high FEL yields is complicated and subject to real operating conditions

Additionally creditable FEL Power interlocks are non-trivial and will require significant work to achieve at appropriate safety integrity levels



Outline

SLAC and LCLS-II-HE Overview

Defining the Scope of Work

Beam Containment Analysis

- Superconducting Beam
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Shielding Analysis

Shielding: SR Sources

Shielding Designed Envelope (SDE) used in Front End Enclosure (FEE) and Hutch Shielding

Goal: Determine if new SR source is less than the Shielding Design Envelope

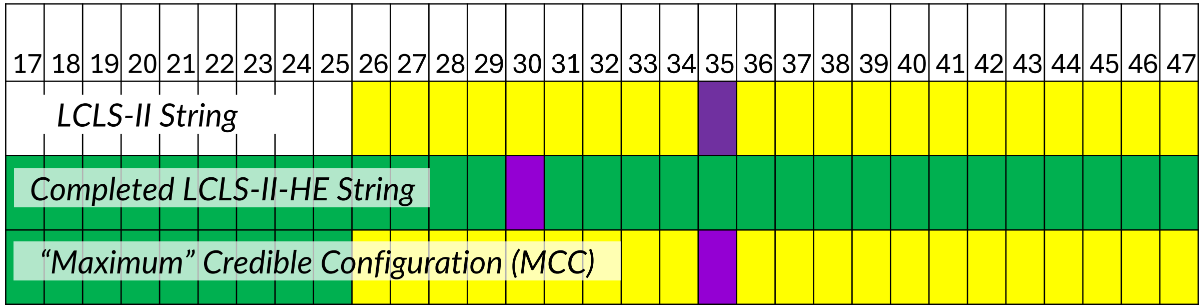
Configuration		Electron Energy	Electron Beam Power
LCLS-SC Operation		5 GeV	120 kW
LCLS-NC Operation		12 GeV	2.6 kW
Shielding Design Envelope	SC:	8 GeV	240 kW
	NC:	20 GeV	5 kW

Factor of 2 higher power already considered

Simulations of SR source spectra were performed with the SPECTRA Code and calculated analytically

LCLS-II SXUs HE SXUs Self-Seeding
(out of scope)

Changes to total SR power



Shielding Design Envelope With **21 LCLS-II SXUs**

- **SC**: 240 kW / 8 GeV → 222 W
- **NC**: 5 kW and 20 GeV → 11.6 W

Proposed Change With **30 HE SXUs**:

- **SC**: 120 kW / 5 GeV → 120 W
- **NC**: 2.6 kW and 12 GeV → 6.2 W

Proposed Change With **9 HE SXUs + 21 LCLS-II SXUs** :

- **SC**: 120 kW / 5 GeV → 105 W
- **NC**: 2.6 kW and 12 GeV → 5.5 W

Shielding design envelope exceeds both the completed LCLS-II-HE Sting and MCC

Conservative assumptions about future performance have enabled this change in operation, with only minimal additional shielding analysis

Summary

LCLS-II-HE project <u>**increases**</u> **the high repetition rate capability of the Hard X-ray Beam at LCLS**, **and** <u>**maintains**</u> **the existing capability** for **Soft X-Ray Science** with the installation of the new Soft X-Ray Undulators

Some takeaways:

Beam Containment

- Achieved and estimated maximum credible FEL yields remains at tension and requires on going dialogue

Shielding

- Previous conservative assumptions enabled major upgrades to scientific infrastructure with only minimal analysis and not additional shielding requirements

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S. Xiao Single Pulse Dose to LCLS-II FEL Stoppers, Collimators and Dumps under SCRF Beams RP-19-07 (2019)

S. Xiao Safety Margin Analyses for LCLS-II FEL Bootstrap RP-22-07-R1(2022)

S. Xiao Radiation Safety System of LCLS-II TMO Beamline RP-20-06-R2 (2023)

S. Xiao Radiation Safety System of LCLS NEH 2.2 FEL Beamline: Design and Implementation RP-20-08-R2 (2023)

H. Wang, S. F. Oller Thermal Studies of CVD Diamond Based FEL Photon Stoppers and Collimators LCLSII-3.5-EN-0772-R2

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Acknowledgement

Work supported by Department of Energy contract DE-AC02-76SF00515

Thank you for listening!

Thank you CNPEM for hosting an amazing RadSynch25

Safe Travels ☺